2011 J. J. Sakurai Prize Address

The Boundless Horizons of Supercollider Physics

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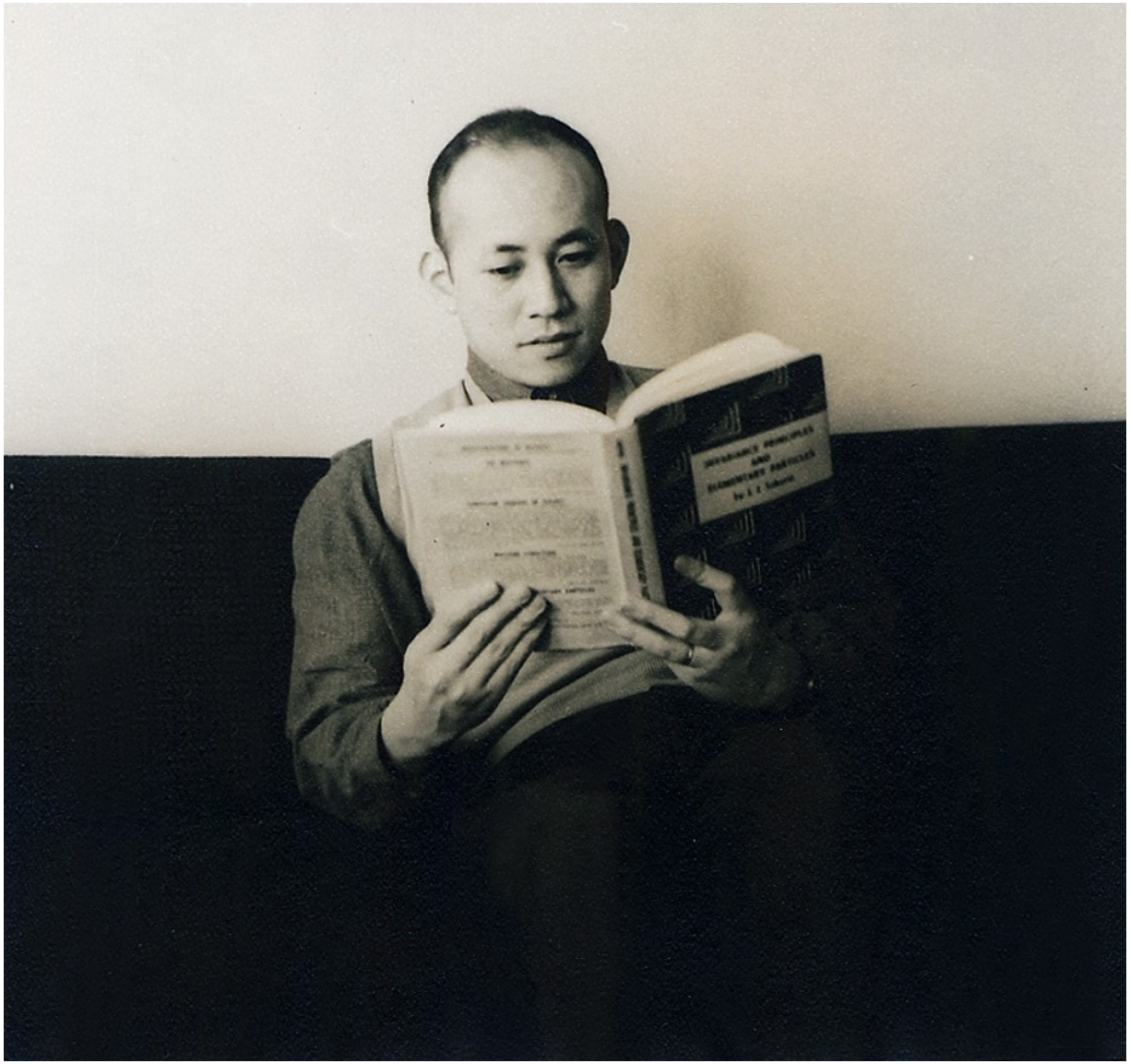
Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

Alexander von Humboldt Stiftung/Foundation

Jun John Sakurai (1933 – 1982)



1965 photo courtesy of Ken Sakurai

John David Jackson (2009)

David Quigg

The importance of the 1-TeV scale

Gedanken experiment: high-energy scattering of

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0/\sqrt{2} \quad HH/\sqrt{2} \quad HZ_L^0$$

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 1 \text{ TeV}$$

condition for perturbative unitarity

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

Instrument of choice: multi-TeV hadron collider

What is a proton?

(For hard scattering) a broad-band, unseparated beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

$$f_i^{(a)}(x_a, Q^2),$$

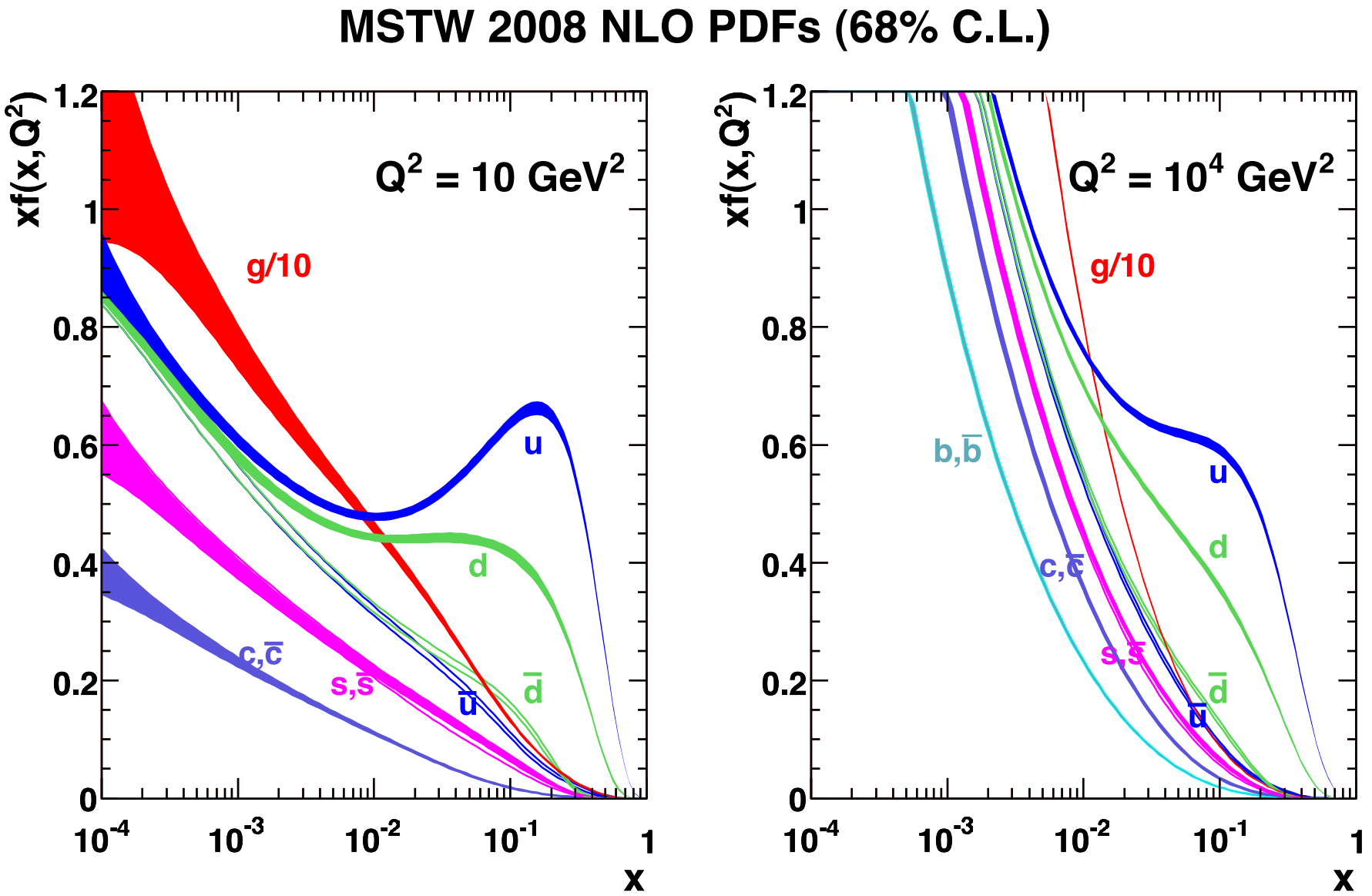
. . . number density of species i with momentum fraction x_a of hadron a seen by probe with resolving power Q^2.

Q^2 evolution given by QCD perturbation theory

$f_i^{(a)}(x_a, Q_0^2)$: nonperturbative

EHLQ: LO, heavy flavors, $Q^2 < 10^8$ GeV^2, $x > 10^{-4}$

Comprehensive PDF determinations at NLO . . .

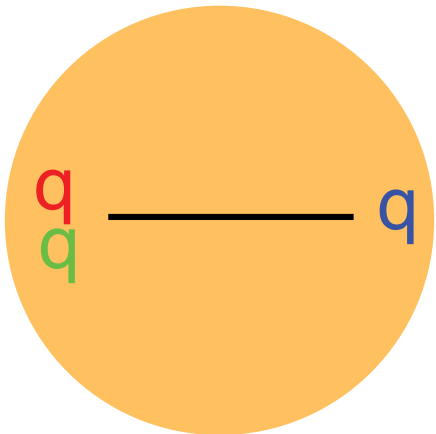


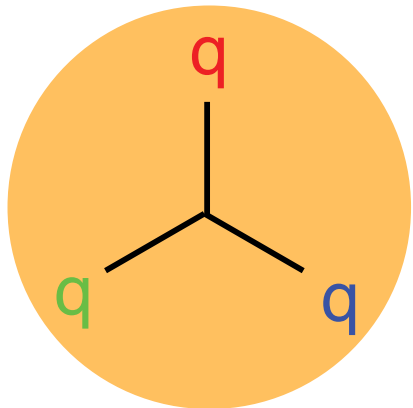
Beyond traditional parton distributions

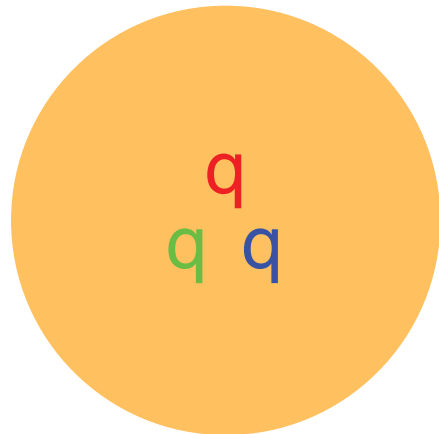
$$f_i^{(a)}(x_a, Q_0^2)$$

No correlations, only longitudinal degrees of freedom

Generalized PDFs, q—(qq) configurations, . . .







Bjorken, 2010

QCD as background and signal

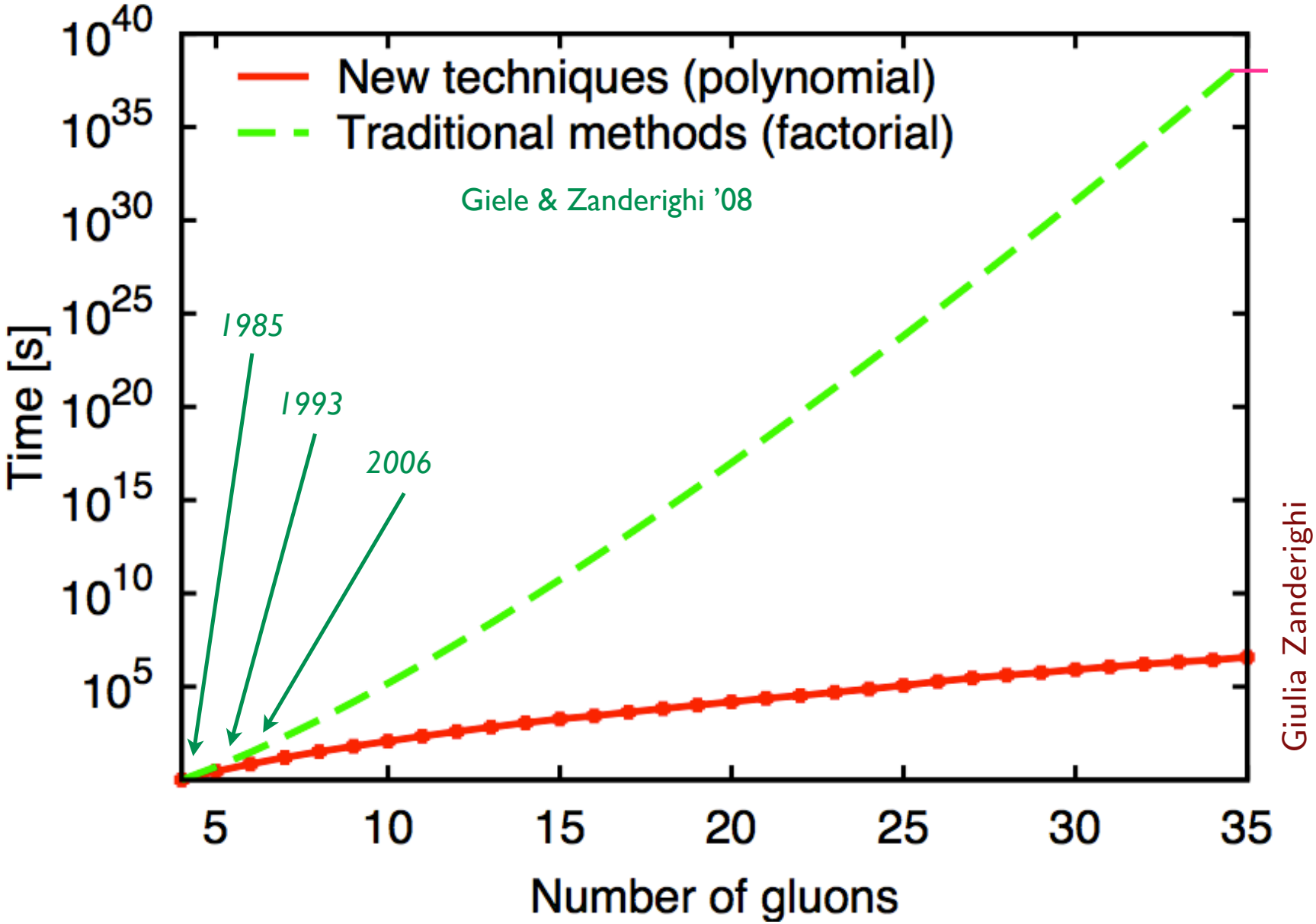
EHLQ focused on dijets, tabulated three-jet cross sections

Would $>$ 6-point amplitudes ever be possible?

1986: Parke–Taylor formula (N gluons at tree level)

Cascade of new techniques, inspired by supersymmetry, stringy methods, recursion, S-matrix style unitarity, seminumerical algorithms, ...

Advances in perturbative QCD: N gluons @ 1-loop



Advances in perturbative QCD:

The acceleration of (pQCD) history

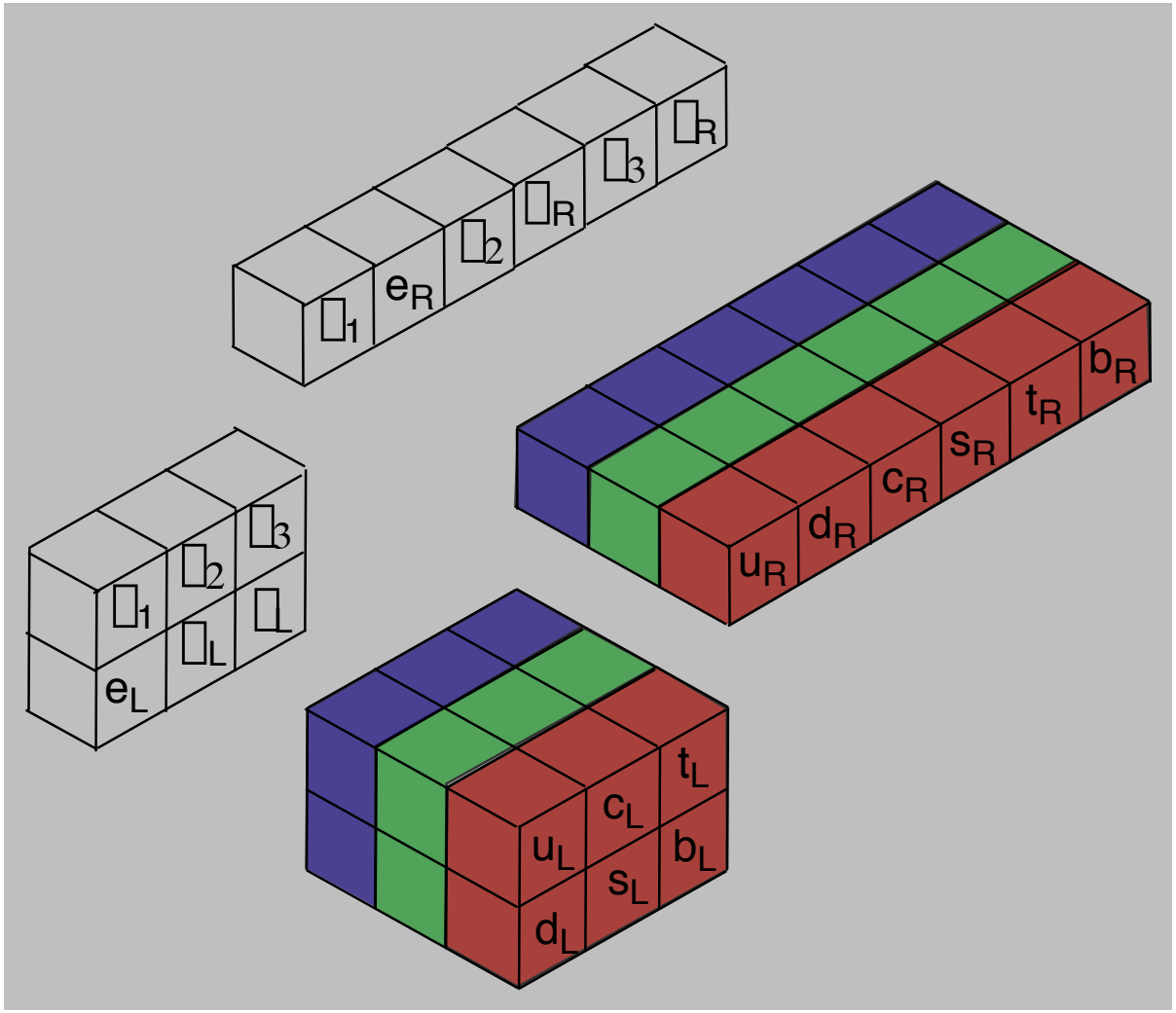
pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa
		Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa

Lance Dixon

cf. Z. Bern, **c2 2**

Our picture of matter

Pointlike ($r \lesssim 10^{18}$ m) quarks and leptons



Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

An unknown agent hides EW symmetry

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

Unanswered Questions in the EW Theory, 0905.3958

Why will it matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

- Electron and quarks would have no mass
- QCD would confine quarks into protons, etc.
  Nucleon mass little changed
- Surprise: QCD would hide EW symmetry, give tiny masses to W, Z
- Massless electron: atoms lose integrity
- No atoms means no chemistry, no stable composite structures like liquids, solids, ...

Very different universe!

CQ + R. Shrock, *Gedanken Worlds* [arXiv:0901.3958]

If we find a Higgs boson . . .

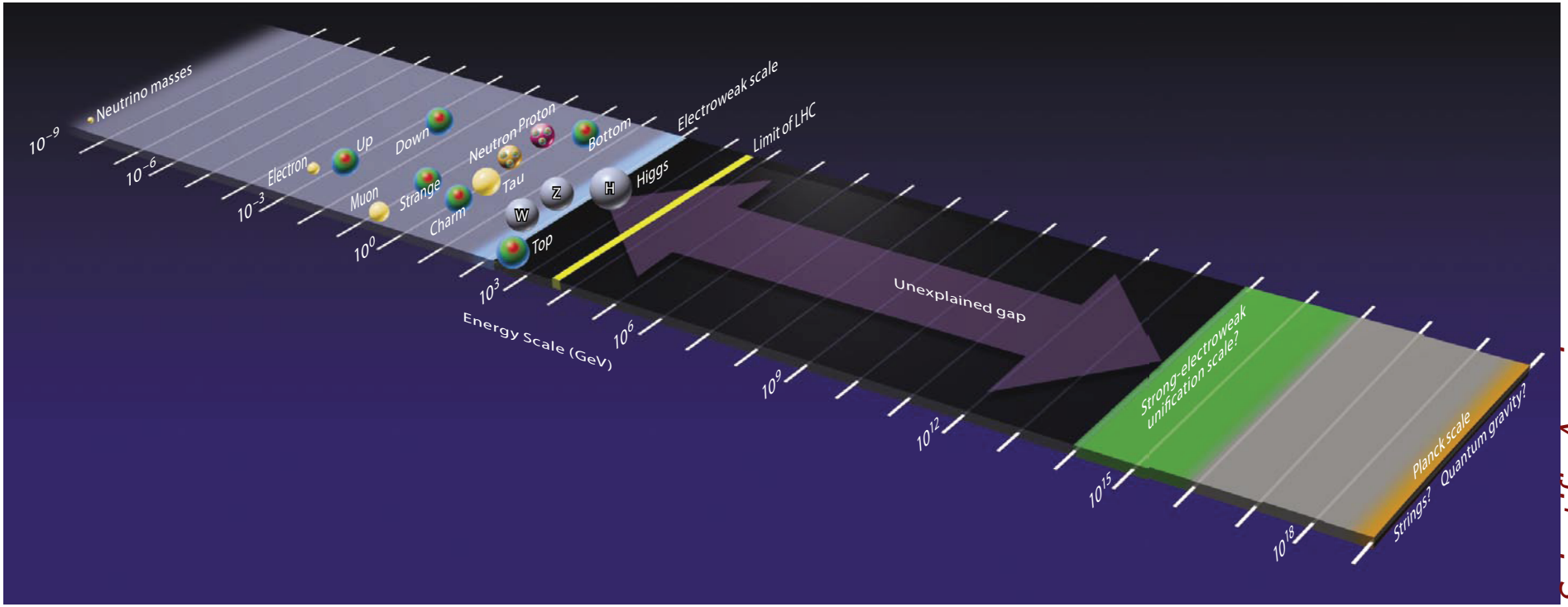
Does it give mass to fermions?

If so, we will learn *why* the muon weighs

We will still not know (in theory) *what* the muon weighs

Fermion mass implies physics beyond the standard model!

The hierarchy problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*

How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*

Why is the electroweak scale small?

Two Puzzles

1: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no sign of flavor-changing neutral currents

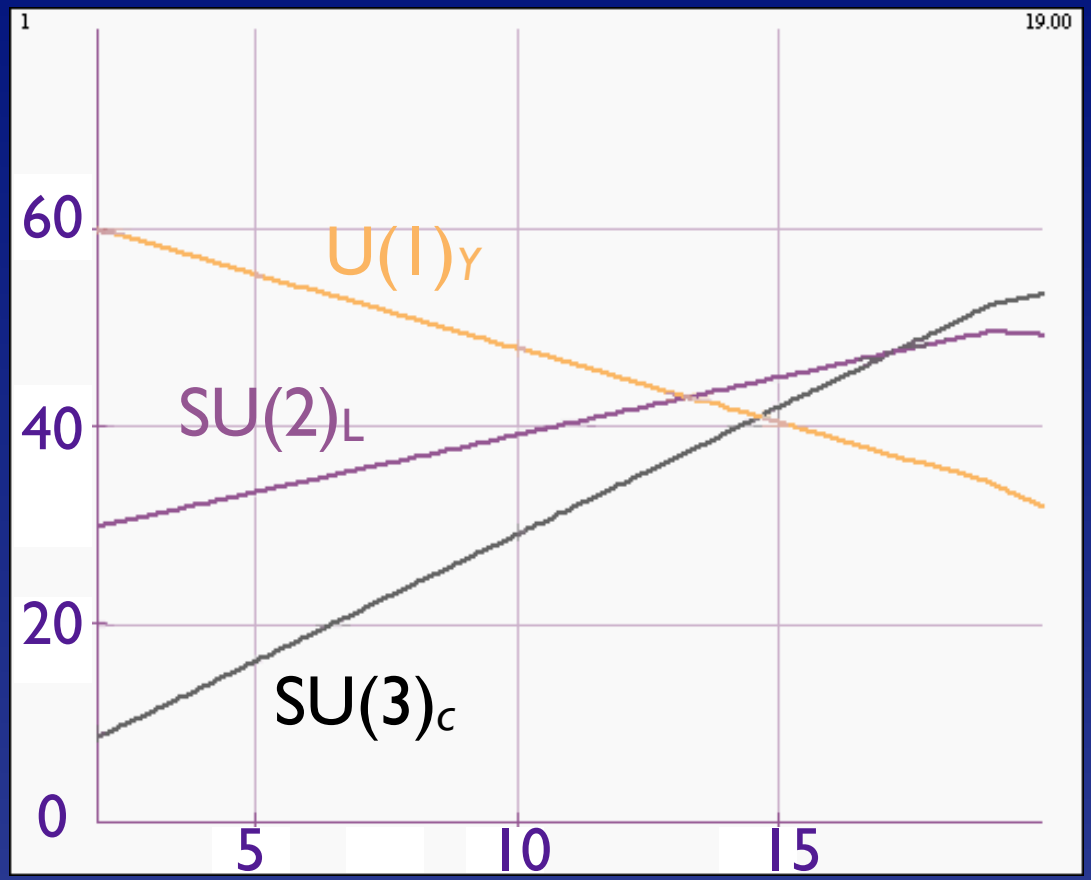
Minimal flavor violation a name, not yet an answer

$\rightsquigarrow$ searches for forbidden or suppressed processes

2: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no certified failures of EW theory

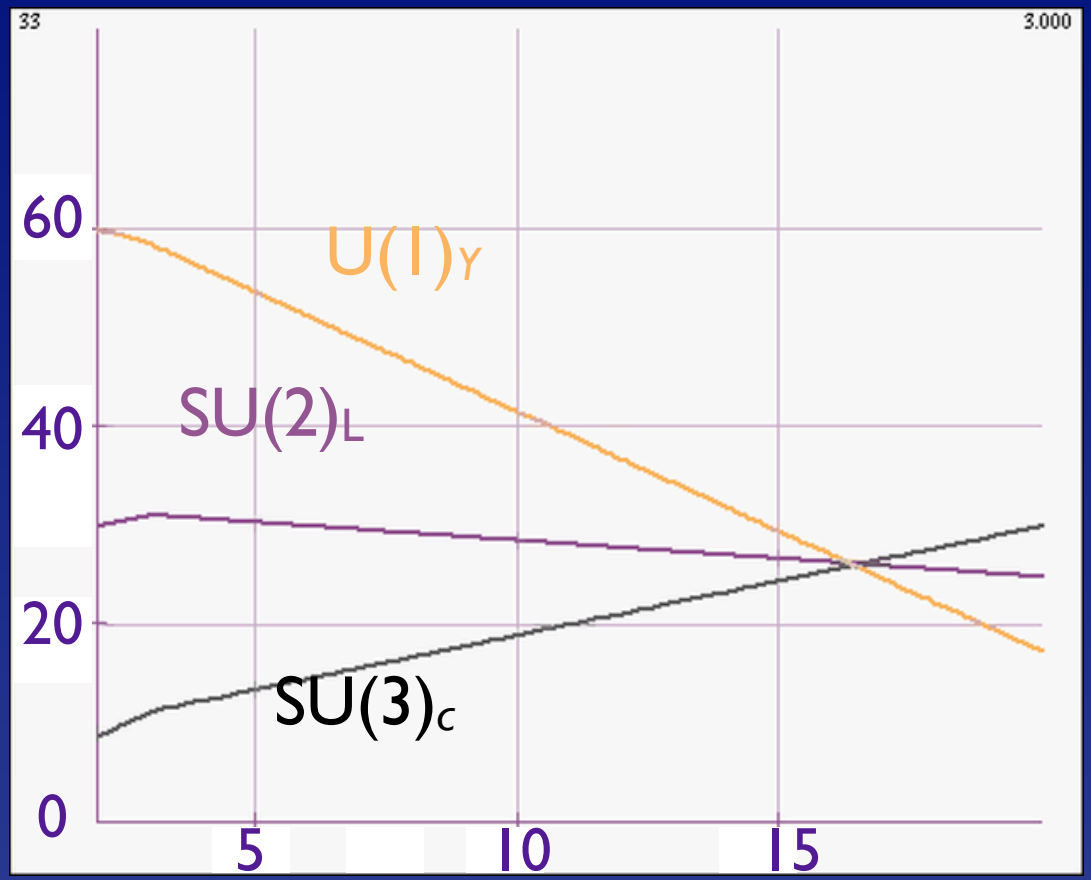
Unified theories: SU(5)

Unification of Forces?



Unified theories: SU(5) + light SUSY

Unification of Forces?



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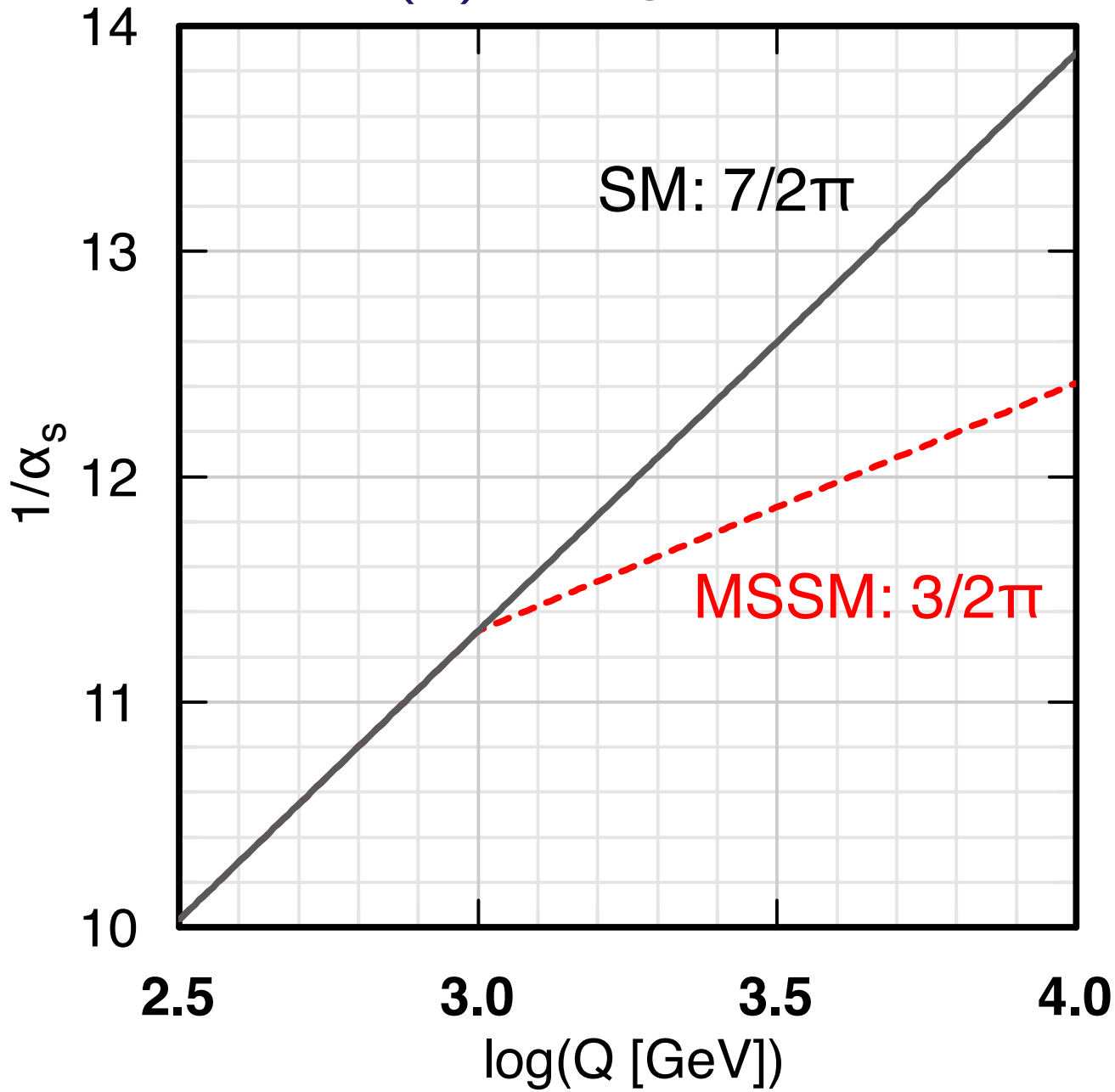

Issues for the Future (Now!)

1. What is the agent of EWSB? Is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?

Issues for the Future (Now!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, …?

20. How are we prisoners of conventional thinking?

Ultreia !

EHLQ (1984)